S282 Astronomy

Optical and X-ray images of clusters of galaxies

Study time: 45 minutes

Summary

In this activity you will analyse optical and X-ray images of five nearby clusters of galaxies. You will compare the appearance of clusters of galaxies in these two wavebands. You will also consider how clusters vary from one another on the basis of their appearance in such images.

You should have read to the end of Section 4.4 of *An Introduction to Galaxies and Cosmology* before starting this activity.

Learning outcomes

- Appreciate the difference in appearance between different cluster types.
- Understand the spatial relationship between cluster galaxies and the intracluster medium.
- Appreciate why clusters are frequently more easily identifiable by their X-ray emission than by visual appearance.

Background to the activity

The five clusters that have been chosen for this activity are well-known nearby rich clusters, all within 200 Mpc of our own Galaxy. The clusters were first documented as part of George Abell's original study as described in Chapter 4 of *An Introduction to Galaxies and Cosmology*. The Abell cluster catalogue numbers are given, together with additional details, in Table 1.

Table 1 Cluster data.

	Abell 2199	Centaurus	Coma	Hydra	Perseus
Distance/Mpc	180	52	110	60	90
RA	16 h 29 min	12 h 49 min	13 h 00 min	10 h 37 min	03 h 20 min
Dec	+39° 33′	−41° 19′	+27° 58′	−27° 30′	+41° 30′
Abell Number	A2199	A3526	A1656	A1060	A0426

The optical images of the clusters are taken from the Digitized Sky Survey (DSS). Archived photographic plates from the Palomar Optical Sky Survey and others have been digitized using a high-resolution scanner, both preserving the data and making it far more widely accessible.

The X-ray images are from the ROSAT (Röntgensatellit) X-ray Observatory. This was a joint German, UK and US mission that was launched in 1990 and operated until 1999. The images were made using an instrument called the Position Sensitive Proportional Counter (PSPC) that had a 2 degree field of view and a spatial resolution of approximately 30 arc seconds.

By contrast, the DSS optical images presented here have a resolution approximately four or five times higher than the X-ray data. The original scans were to a much higher resolution still, but the images used here have been scaled down in order to fit the whole image on screen. Even so, the optical images are visibly more detailed than the X-ray images, and you should bear the difference in resolution in mind when comparing the images.

Part 1 A comparison of optical images

This first part of the activity concentrates on the visual aspects of the DSS images. You will compare similarities and differences between the Digitized Sky Survey images of the five clusters.

- Start the S282 Multimedia guide and open the folder called 'Galaxies', then click on the icon for this activity (Optical and X-ray images of clusters of galaxies).
- Press the Start button to access the set of cluster images. Images of different clusters can be selected using the buttons that are displayed on the right-hand side of the screen (Figure 1).

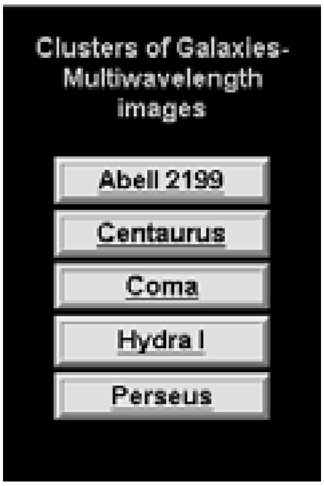

Figure 1 The selection buttons for the cluster images.

You are going to start by looking at the *optical* images for each of the five clusters. (Note that in this image set the term 'visible' has been used to denote optical observations at visual wavelengths. We shall refer to these as the 'optical' images in these notes.)

- Start by clicking on the Abell 2199 button at the top of the list on the right-hand side of the screen. An optical image of the Abell 2199 cluster will be displayed in the left-hand pane.

The first thing to notice is that the image is presented as a *negative*. This is the view that you would get if studying traditional photographic plates on a light box. Take a while to look carefully at the image and get used to the appearance of the different objects in the image.

- Now click on the other four buttons to display the Centaurus, Coma, Hydra I and Perseus clusters in turn, and note the appearance of these clusters. In each case, take a moment to study the image and note the different types of objects present in each image.

(Note that there are slight differences in the image scales: the images of the Centaurus, Coma and Hydra clusters are all 1.0 degrees to a side, whereas the Perseus image is 1.5 degrees across and the image of A2199 is 0.75 degrees wide.)

The images contain many foreground stars within our Galaxy and it is important to be able to distinguish between these and galaxies.

■ Can you identify which of the objects in each image are galaxies and which are stars? How would you describe the differences between the appearance of the stars and galaxies?

❑ The galaxies are extended objects with bright cores surrounded by diffuse regions, whereas the majority of the stars are point-like objects. Many of the galaxy images are non-circular in outline, whereas stars should appear circular. Elliptical galaxies will always appear as either diffuse circles or ellipses. Spirals may appear face-on, edge-on or at an angle.

Brighter stars can appear as extended sources, but these can be distinguished by a sharper edge and the presence of diffraction spikes which give the star a cross-like appearance. The difference between bright stars and galaxies can be seen most easily in the image of Hydra I. Here the central region contains two very bright stars (see Figure 2), along with several spiral and elliptical galaxies of differing shapes and sizes. A large number of fainter stars appear as sharp points.

When comparing galaxies from different clusters, it is necessary to take into account the relative distances of the clusters as shown in Table 1. There are also small differences in the angular scales of the images.

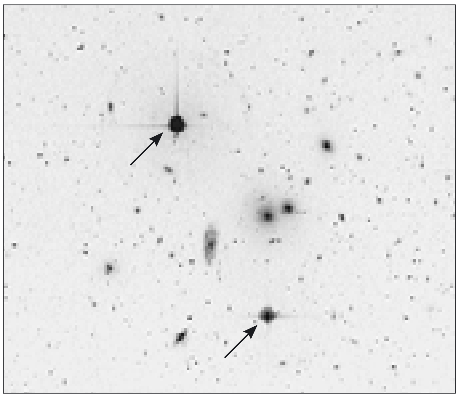

Figure 2 Foreground stars in the image of the Hydra I cluster.

Question 1

Because the clusters are at different distances, and some of the images have differing angular scales, galaxies of the same actual size will appear at different (angular) sizes on the different images. In order to compare the images properly, it is necessary to know the physical scales of the images.

Using the information in Table 2, calculate the width (in Mpc) of the field of view at the distance of each cluster and hence complete the table.

How do these distances across the field of view compare to the Abell radius. What implications does this have for your comparison of the clusters?

Table 2 Fields of view for the clusters of galaxies in the image set.

	Abell 2199	**Centaurus**	**Coma**	**Hydra I**	**Perseus**
distance/Mpc	180	52	100	60	90
angular width of image/degree	0.75	1.0	1.0	1.0	1.5
width of the field of view/Mpc					

The importance of allowing for the different scales of the images that you worked out in Question 1 is highlighted in the following example. Most of the galaxies appear quite small in the image of Abell 2199. This is largely due to the fact that, at 180 Mpc, Abell 2199 is the most distant of the five clusters. If the images of Abell 2199 and the Hydra I cluster are re-sized so that they have the same scale (Figure 3) then a comparison between the galaxies in the two clusters can be made. The central galaxy of Abell 2199 (NGC 6166) is a supergiant elliptical galaxy, and is actually much larger than the central galaxies in the Hydra image.

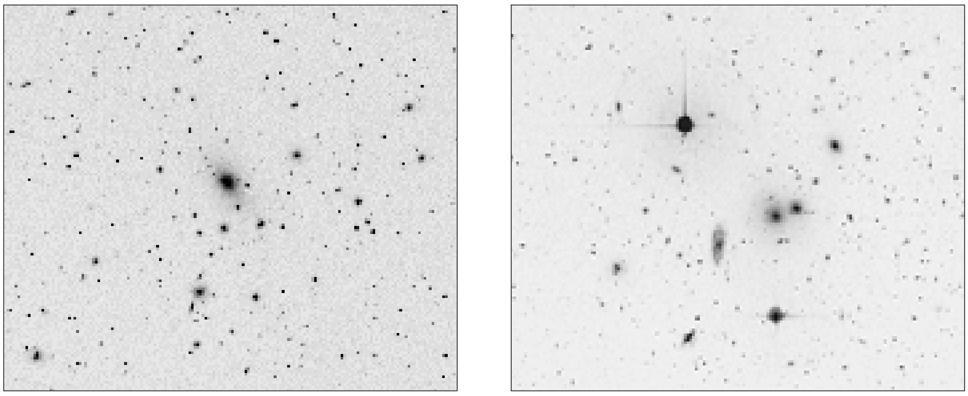

Figure 3 Comparison of central regions of the (left) Abell 2199 and (right) Hydra I clusters. The image of Abell 2199 has been corrected for distance and scale to enable the relative sizes of the galaxies to be compared. At 20 times the diameter of the Milky Way, NGC 6166 is one of the largest known galaxies.

Question 2

Using the selection buttons review each cluster image again in turn, starting with A2199. In each case, write one or two brief sentences describing the overall appearance of the cluster. Describe the relative sizes of the fields of view (Question 1), and the distribution and types of galaxies present.

As mentioned in Chapter 2 of *An Introduction to Galaxies and Cosmology*, galaxies come in a wide range of sizes: most of the clusters appear to have just one or two very large central galaxies with numerous smaller ones.

- Are all of the smaller galaxies visible in the images genuine cluster members? How would you determine whether any of the galaxies are actually *field galaxies* that only appear in the image through being on the same line of sight as the cluster?

- ❑ Field galaxies are galaxies that are not physically associated with the cluster and actually lie at different distances. Since galaxies vary greatly in size, it is difficult to tell the distance of a galaxy from its (angular) size on the image. The best way to determine the distance of a galaxy is to measure its redshift, so spectral measurements could be used to identify field galaxies and separate them from the genuine cluster members.

Part 2 A comparison between optical and X-ray images

Now we are ready to start comparing the optical and X-ray appearances of the clusters. In this part of the activity we will concentrate on the general differences between the images taken in the optical and X-ray wavebands for all five clusters.

The Navigation Menu (Figure 4) on the lower right-hand side of the screen allows you to select four different views of each cluster. The left-hand column, headed Image allows you to choose between optical or X-ray views of the cluster. In the right-hand column you can select the same two views with a contour plot of the X-ray intensity superimposed.

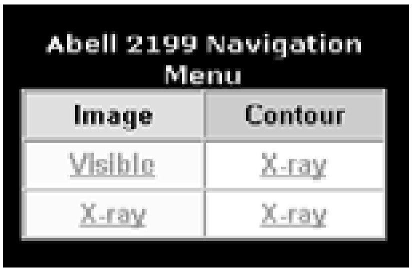

Figure 4 The navigation menu.

- Select Abell 2199 using the cluster selection buttons and then click on X-ray in the left-hand column of the navigation menu. The X-ray image of Abell 2199 will be displayed.
- By clicking on Visible and X-ray in the left-hand column you can flip between the two images to compare the appearance of the cluster in the two different wavebands.
- By clicking the links in the right-hand (Contour) column, either the optical or the X-ray image of each cluster can be displayed with a contour plot of the X-ray emission overlaid. This will help you to compare the regions of emission.
- Now select each of the clusters in turn and compare the optical and X-ray images of all five clusters.

Question 3

Describe in a sentence or two the general similarities or differences between the X-ray images and the optical images. Is there any correspondence between the areas of X-ray emission and the positions of the individual galaxies? Is it likely that the galaxies are the source of the X-ray emission?

Question 4

What is the origin of the X-rays from the cluster, and what does this imply about the structure of the clusters as a whole? (You may need to refer to Chapter 4 of *An Introduction to Galaxies and Cosmology* to answer this question.)

Each of the images in this activity covers a very small field of view (approximately 1 degree square). Now imagine that, instead of these five images centred on known clusters, you are planning to carry out a wide-field survey of a large area of sky in order to find clusters of galaxies.

Question 5

What would be the advantage of conducting a survey to detect clusters from their X-ray rather than their optical emission?

Although the answer to Question 5 might suggest that it should be easy to detect clusters from their X-ray emission – the sensitivity of X-ray telescopes limits the application of this technique. However, one example of such a survey is the Northern ROSAT All-Sky Galaxy Cluster Survey (NORAS), which was carried out using the same PSPC instrument used to take the X-ray images in this activity.

Another problem that has to be overcome in X-ray surveys is that clusters of galaxies are not the only X-ray sources in the sky.

Question 6

What other objects might also appear as bright X-ray sources? How would you exclude these sources from an X-ray survey? (*Hint*: think about the areas of the sky that should be covered in such a survey and the behaviour of other X-ray emitting sources.)

Answers to questions

Question 1

The formula $l = d \times \theta$ (where d is the distance to the cluster, θ is the angular width of the image in radians, and l is the width of the image in Mpc) can be used to calculate the width of each image. For example, the width of the field of view of Abell 2199 is l = 180 Mpc × 0.75° × (1/57.3) = 2.4 Mpc.

The completed Table 2 is given in Table 3.

Table 3 Fields of view for the clusters of galaxies in the image set.

	Abell 2199	Centaurus	Coma	Hydra I	Perseus
distance/Mpc	180	52	100	60	90
angular width of image/degree	0.75	1.0	1.0	1.0	1.5
width of the field of view/Mpc	2.4	0.9	1.7	1.0	2.4

The Abell radius R_A is 2 Mpc. A typical cluster would therefore have a diameter of 4 Mpc. It follows that only the central region of the clusters is shown.

Question 2

Suitable descriptions of the images would be as follows:

Abell 2199 – This is a relatively wide-field image of a distant cluster. There is one large central galaxy with numerous smaller galaxies quite widely spaced. Some of the smaller galaxies appear to be spirals.

Centaurus – This is a relatively narrow field of view of a nearby cluster. There is one large elliptical galaxy at the centre with another large elliptical to the left of centre. The surrounding galaxies appear to contain both ellipticals and spirals.

Coma – This cluster is at intermediate distances compared to the other clusters in the sample. The field of view is relatively wide. There are two large ellipticals surrounded by smaller galaxies. It appears to be a little more tightly packed than A2199. Again some of the smaller galaxies appear flattened. (Although it is not possible to determine morphological types from these images – they are, in fact, mainly highly flattened elliptical galaxies rather than spirals.)

Hydra I – As in the case of Centaurus, this is a relatively narrow field of view of a nearby cluster. The cluster has a tight nucleus of several large galaxies, including one large spiral and a number of other spirals present.

Perseus – The field of view and distance are comparable to the image of the Coma cluster. There are two large central elliptical galaxies and the surrounding galaxies appear to be widely separated. The surrounding galaxies appear to be mainly ellipticals with no obvious spiral galaxies.

Question 3

In each case the area of X-ray emission is much larger than the individual galaxies that are visible in the optical images. The X-ray emission area forms a broad, roughly elliptical envelope surrounding the central galaxies in the cluster. The intensity of X-ray emission is strongest at the centre and falls away smoothly, so that the emission region does not have a sharply defined edge. The X-ray emission does not correspond to individual galaxies but instead appears centred on the centre of mass of the whole cluster. In each case, the X-ray emission region is roughly symmetrical and follows the overall distribution of galaxies, being densest near the centre of the cluster. From these images it seems very unlikely that the galaxies are the source of the X-ray emission.

Question 4

Most of the X-ray emission comes from the space in between the galaxies. The X-rays are not produced within the galaxies, but are the result of *thermal bremsstrahlung* from the intracluster medium (ICM). Since the X-ray emission comes from such an extended region, we can see that the ICM fills the entire volume of the cluster, forming a cloud within which individual galaxies are embedded. The densest and hottest part of the ICM is at the centre. (The process of thermal bremsstrahlung is described in Box 4.1 of *An Introduction to Galaxies and Cosmology*.)

Question 5

In an X-ray image, a cluster would appear as an extended source of X-ray emission against a darker background, and would be easy to see. In an optical image there are large numbers of field galaxies to contend with: to identify a cluster you would need to filter these out and then look for higher than usual concentrations of galaxies. The individual galaxies are also much smaller than the X-ray emission regions, which makes identifying and counting them a more difficult task. The likely locations of clusters would therefore be much more easily identified on a wide-field X-ray image.

Question 6

The other X-ray sources that may be detected can be classified as being either within our Galaxy (Galactic) or external to our Galaxy (extragalactic). The brightest galactic sources would be supernova remnants and X-ray binaries. However, these are objects that tend to be located close to the Galactic plane (see Figure 9.16 of *An Introduction to the Sun and Stars*), and so by carrying out a survey at high Galactic latitudes – away from the Galactic plane – it is possible to avoid most of these sources. The most prominent extragalactic X-ray sources would be AGN, although the X-ray emission from some nearby normal galaxies might also be detected. Extragalactic sources are less easy to exclude than sources within the Galaxy – but the fact that nearby clusters should be extended sources rather than point-like, means that they should be easy to recognize. More distant clusters, whose angular size is below the resolution of the X-ray telescope are more difficult to identify. However, if such an X-ray source was observed to be variable, then that could not be a cluster – since cluster X-ray emission does not change on short timescales (such a source is likely to be an AGN). Ultimately, any unresolved and unvarying X-ray sources would have to be identified by taking an optical spectrum. The presence of strong emission optical lines would clearly reveal the presence of an AGN.

Acknowledgements

Figure 2 and 3(right), and DVD (Hydra I, Centaurus) Based on photographic data obtained using The UK Schmidt Telescope. The UK Schmidt Telescope was operated by the Royal Observatory Edinburgh, with funding from the UK Science and Engineering Research Council, until 1988 June, and thereafter by the Anglo-Australian Observatory. Original plate material is copyright © the Royal Observatory Edinburgh and the Anglo-Australian Observatory. The plates were processed into the present compressed digital form with their permission. The Digitized Sky Survey was produced at the Space Telescope Science Institute under US Government grant NAG W-2166.

Figure 3(left) and DVD (Abell 2199, Coma, Perseus) Based on photographic data obtained using Oschin Schmidt Telescope on Palomar Mountain. The Palomar Observatory Sky Survey was funded by the National Geographic Society. The Oschin Shmidt Telescope is operated by the California Institute of Technology and Palomar Observatory. The plates were processed into the present compressed digital format with their permission. The Digitized Sky Survey was produced at the Space Telescope Science Institute (ST ScI) under U.S. Government grant NAG W-2166.